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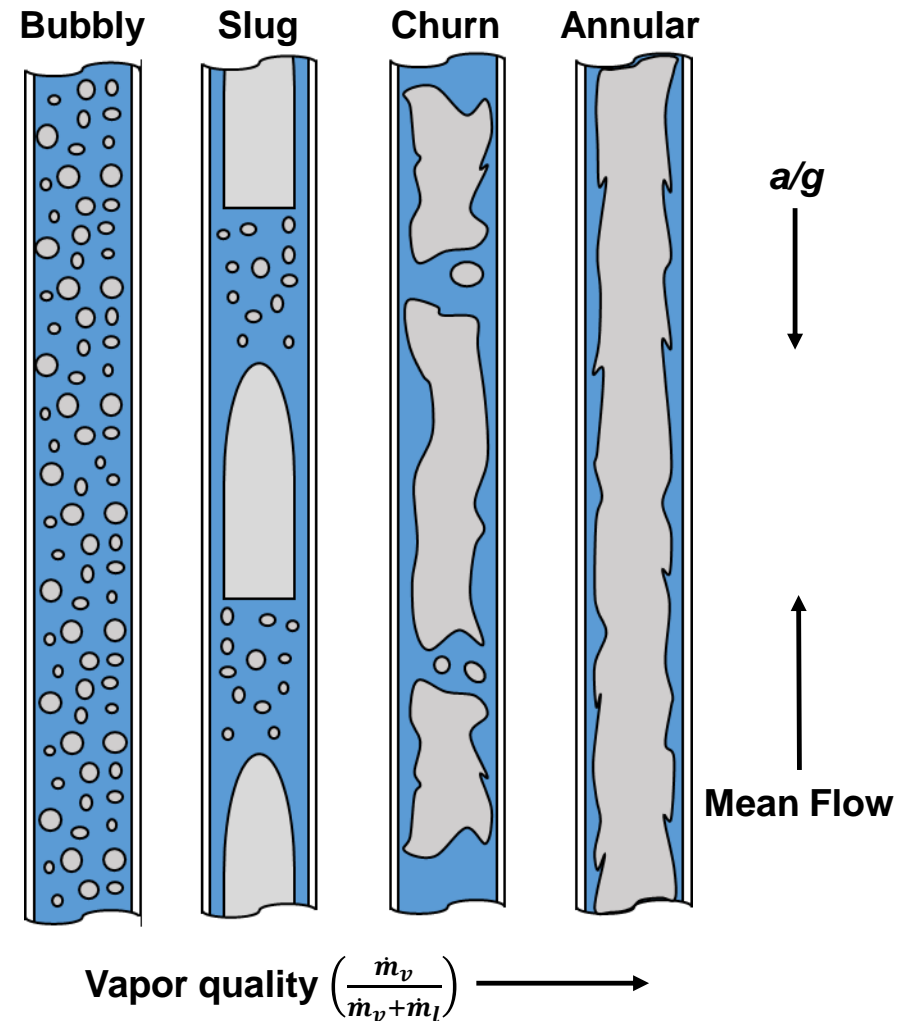
The Effect of Gravity on Single Vapor Elongated Bubbles

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- Flow boiling combines liquid latent heat and convection to improve heat transfer efficiency
- Application of two-phase technology to space systems is desired, but better heat transfer predictions are needed
- Mechanistic heat transfer models may serve as an improvement over traditional empirical correlations
- This work was aimed at identifying the heat transfer mechanisms for the slug flow regime

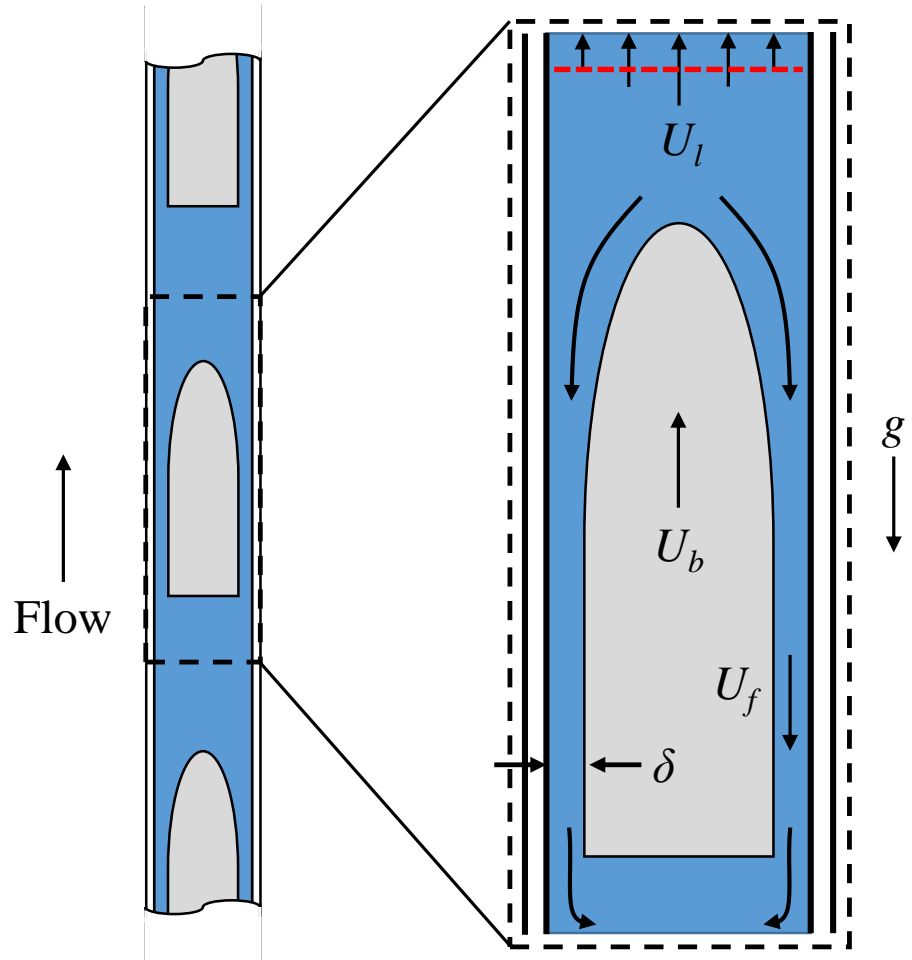


- Fluid motion

- Drift velocity of bubble requires liquid to move to trailing slug
- Steady liquid film formed as wall shear balances with gravitational force
- Circular jet diffuses into slug causing vortices

- Define

- U_l – average liquid velocity
- U_b – bubble velocity
- U_f – liquid film velocity
- U_d – drift velocity, $U_b - U_l$
- δ – liquid film thickness

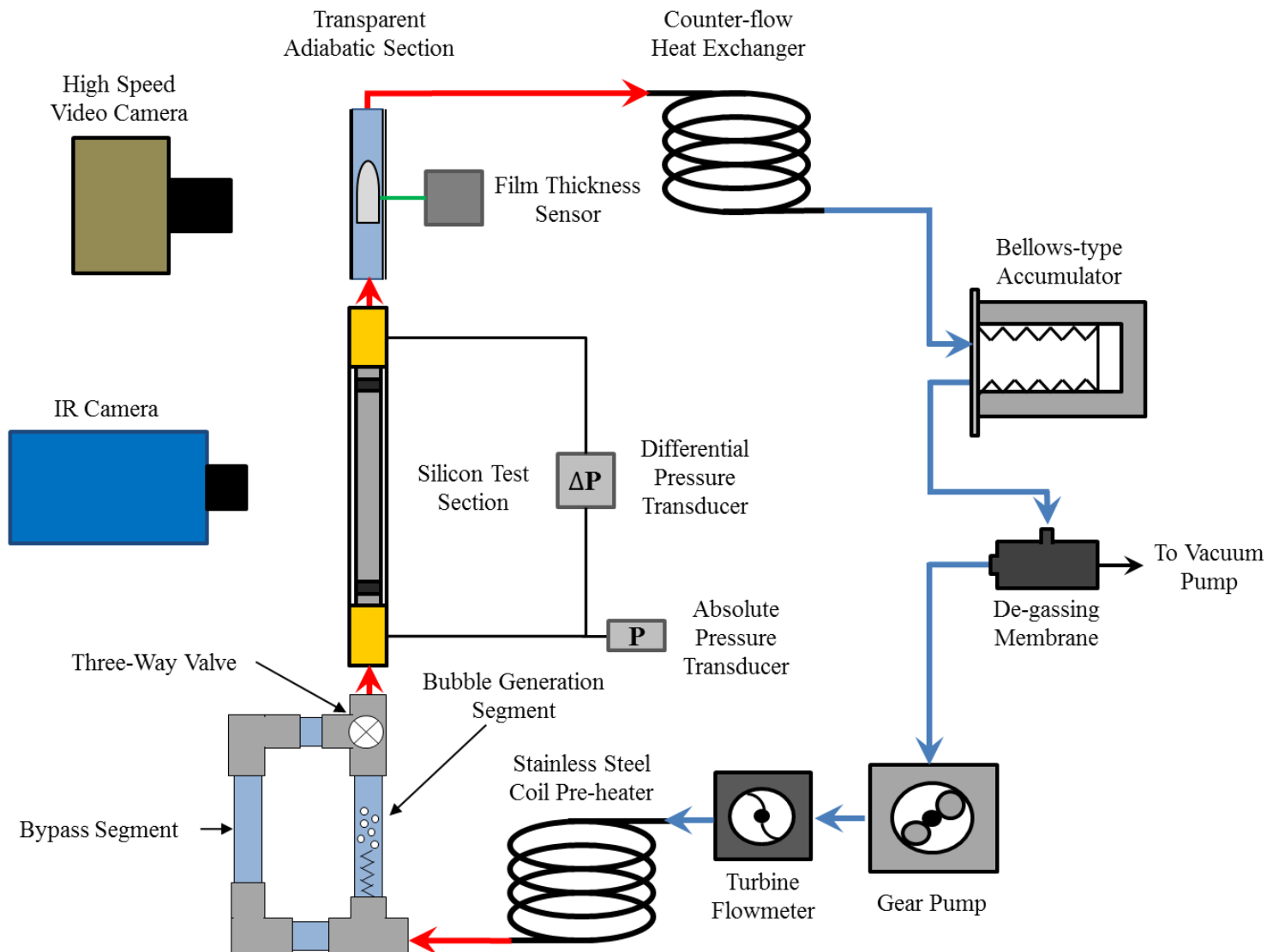


UMD Variable Gravity Flow Boiling Experiment

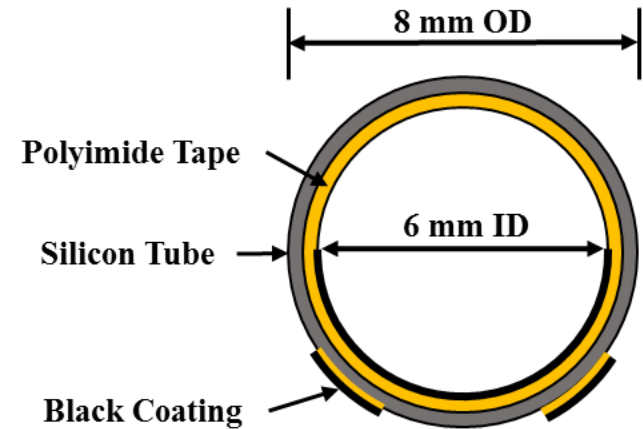
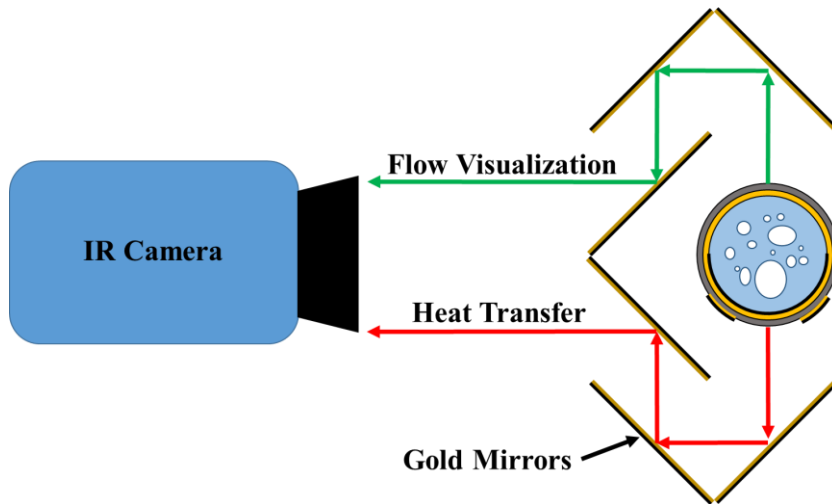
- Designed for parabolic flight testing
- Working fluid – HFE 7100
 - $T_{sat} = 60^{\circ} \text{ C}$ at 1 bar
 - $\mu_l = 0.38 \text{ cP}$ (water: 1 cP)
 - $\sigma_l = 0.013 \text{ N/m}$ (water: 0.073 N/m)
- Measurements available
 - Local heat transfer
 - High-speed flow visualization
 - Film thickness



Flow Loop

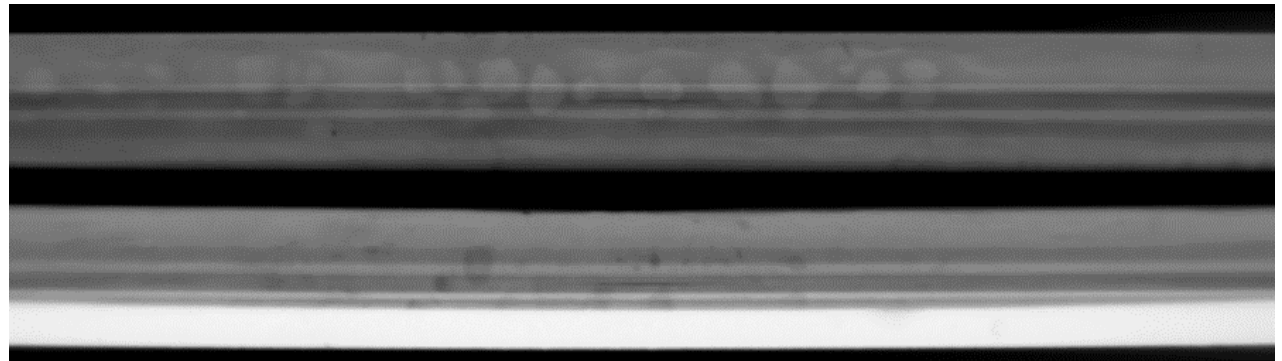


IR technique from Kim et al. (2012)



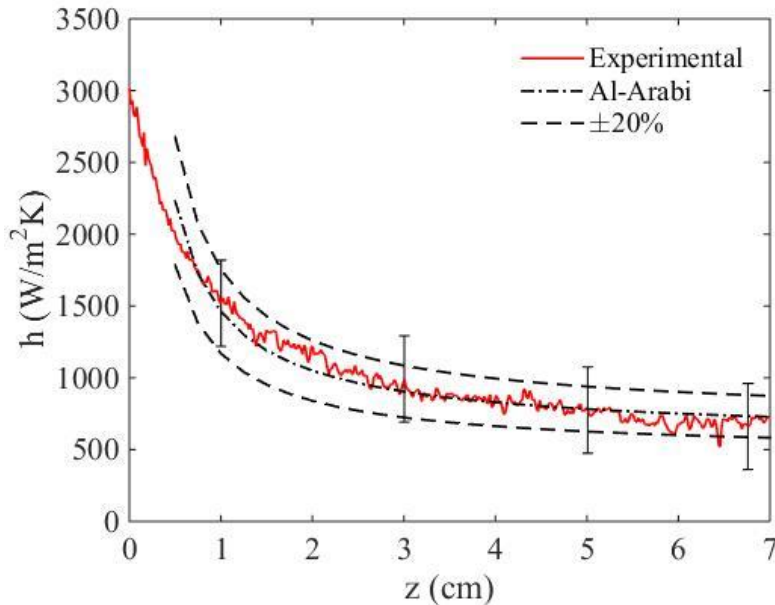
Flow Visualization

Wall Temperatures



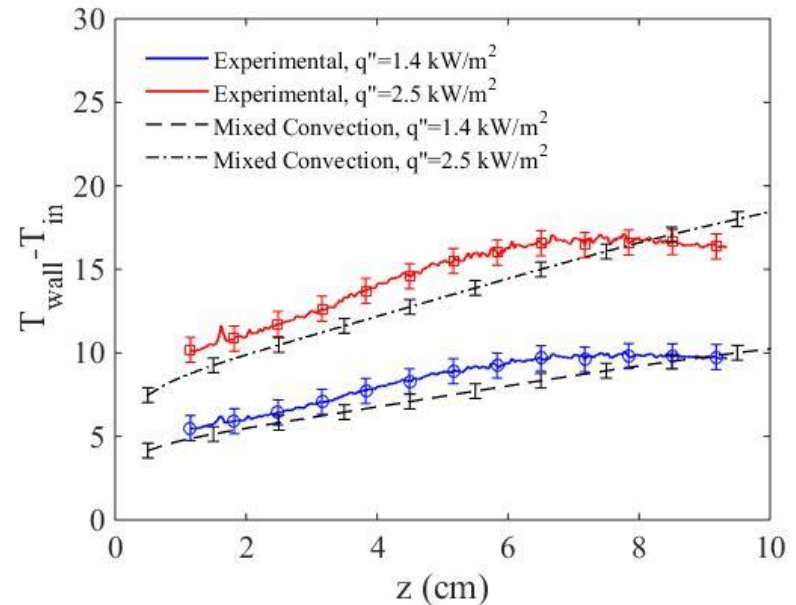
Single-Phase: Turbulent Flow

$Re=5545$, $T_{sub}=20^\circ\text{C}$, $q''=20\text{ kW/m}^2$



Single-Phase: Laminar Flow

$Re=790$, $T_{sub}=20^\circ\text{C}$, $q''=1.4, 2.5\text{ kW/m}^2$



Experimental heat transfer coefficient compared to:

- Dittus-Boelter correlation with Al-Arabi (1982) correction for thermal entry length
- Thermally developing mixed convection correlation (Shah & London, Davis & Perona)

- Studied single, elongated vapor bubbles
- Ground and parabolic flight experiments
- Why variable gravity?

→ Wider range of drift velocities

$$U_d = U_b - U_l = (C - 1)U_l + U_{b,0}$$

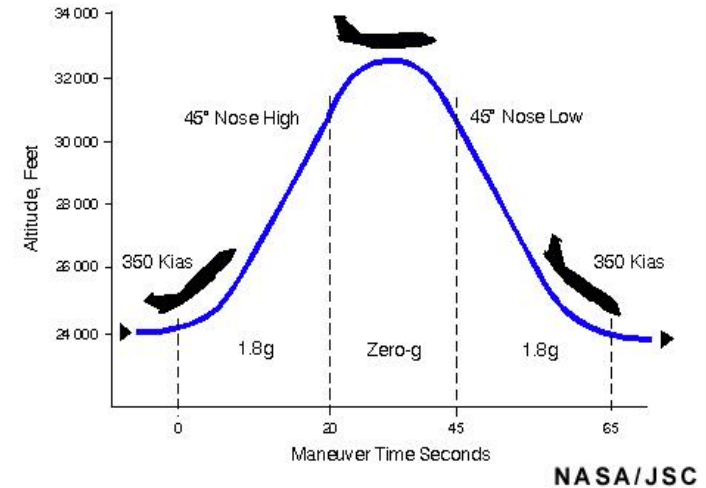
$$\rightarrow U_{b,0} = f(\Delta\rho_{l,v}, g, \mu_l, \sigma_l, D)$$

- Conditions:

- $G = 50 - 200 \text{ kg/m}^2\text{s}$
- $Re_l = 790 - 3090$
- $q'' = 800 - 1700 \text{ W/m}^2$
- $a/g = 0.01, 0.34, 1, \text{ and } 1.8$
- $Bo = \frac{(\rho_l - \rho_v)gD^2}{\sigma} = 0.5 - 87$

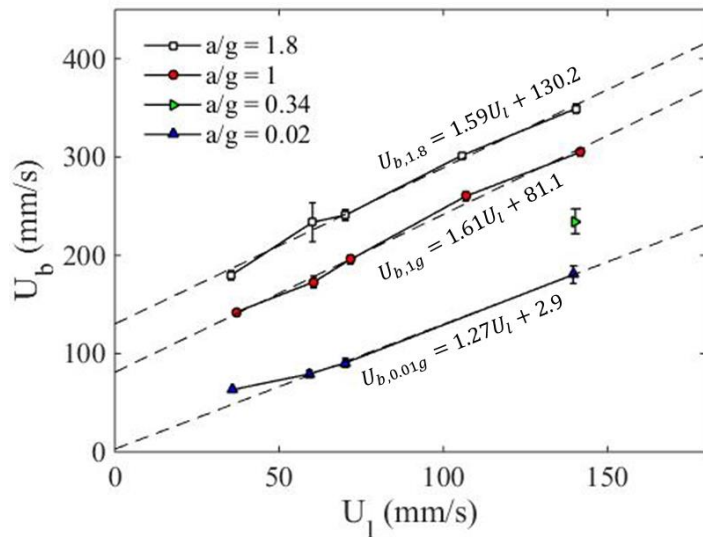
→ Micro/Macro-channel threshold: $Bo=0.9-19.7$

→ Capillary and Taylor bubbles



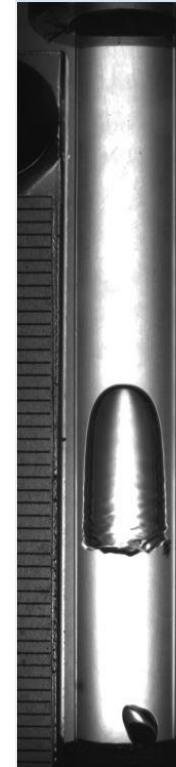
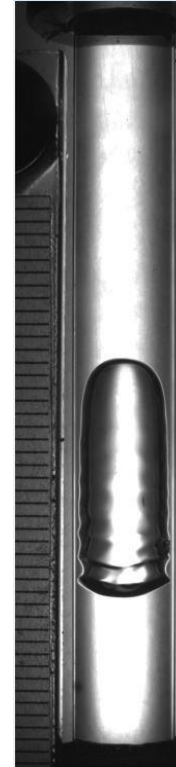
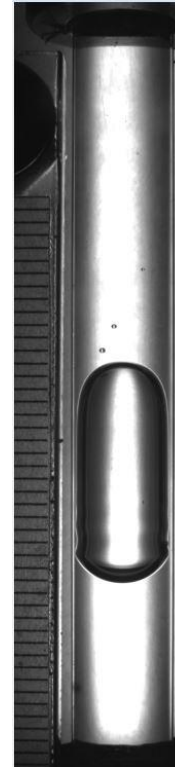
NASA C-9 Aircraft

Bubble Velocity



Buoyancy Term Comparison

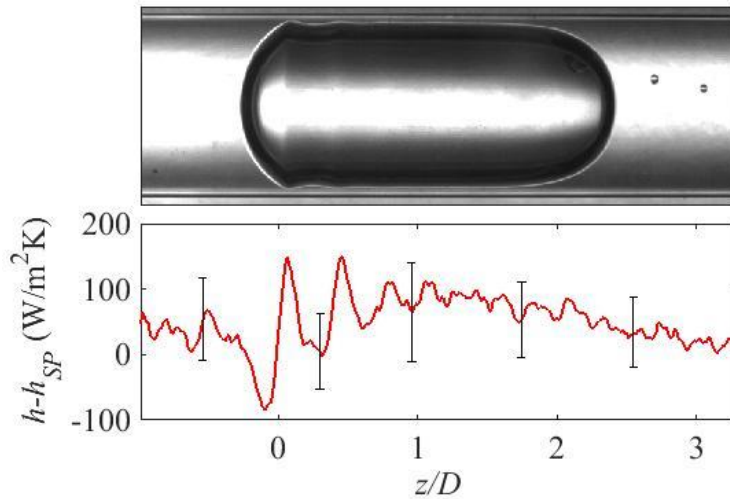
a/g	Current Study	White and Beardmore (1962)	Viana et al. (2003)	Rattner and Garimella (2015)
0.01	3±6	0	—	0
1	81±4	80	82	72
1.8	130±9	112	111	109



Re_l	1525	3051	3051	3051
a/g	0.01	0.01	0.34	1.8
U_d	20 mm/s	41 mm/s	94 mm/s	214 mm/s

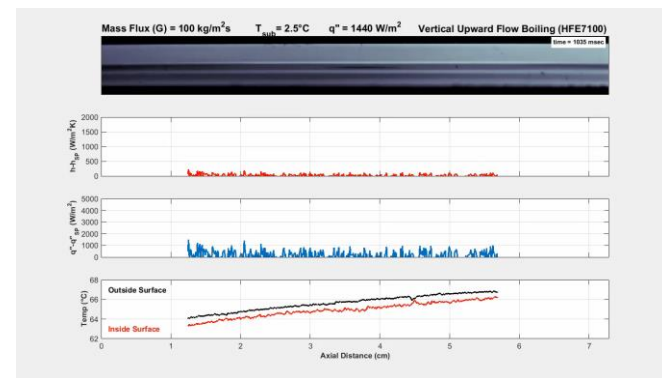
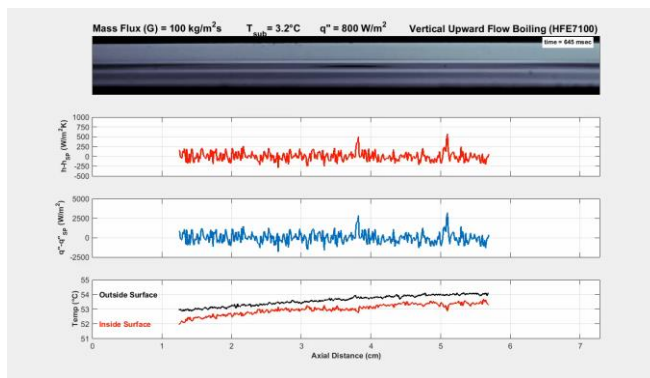
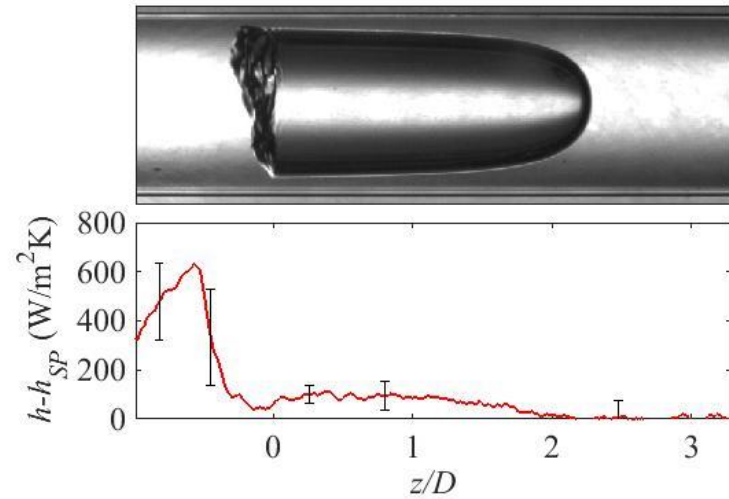
0.01g

$Re=1525$, $U_d=20$ mm/s, $q''=1.1$ kW/m²

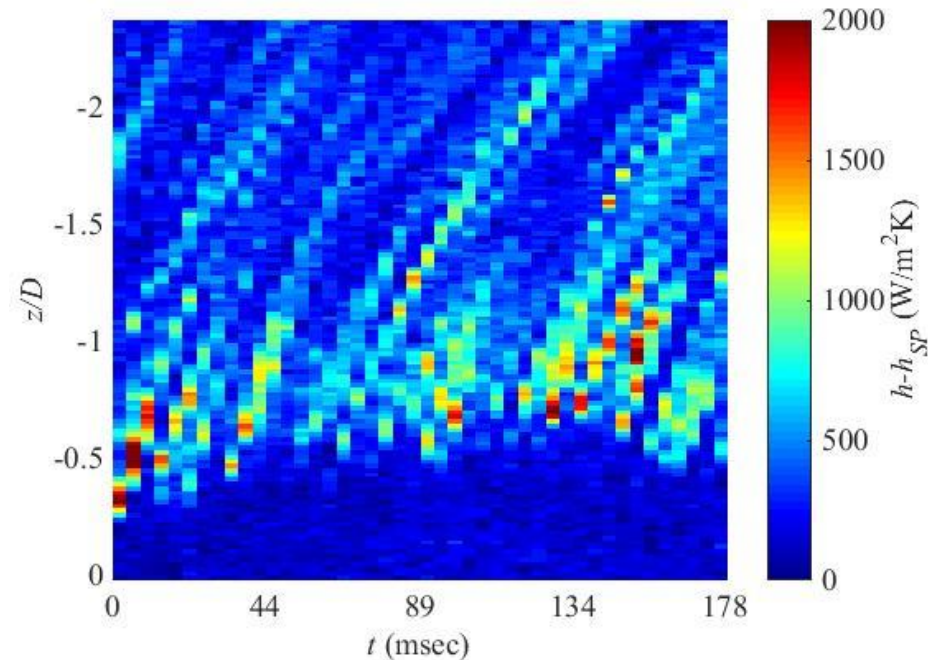


1g

$Re=1525$, $U_d=124$ mm/s, $q''=2.2$ kW/m²

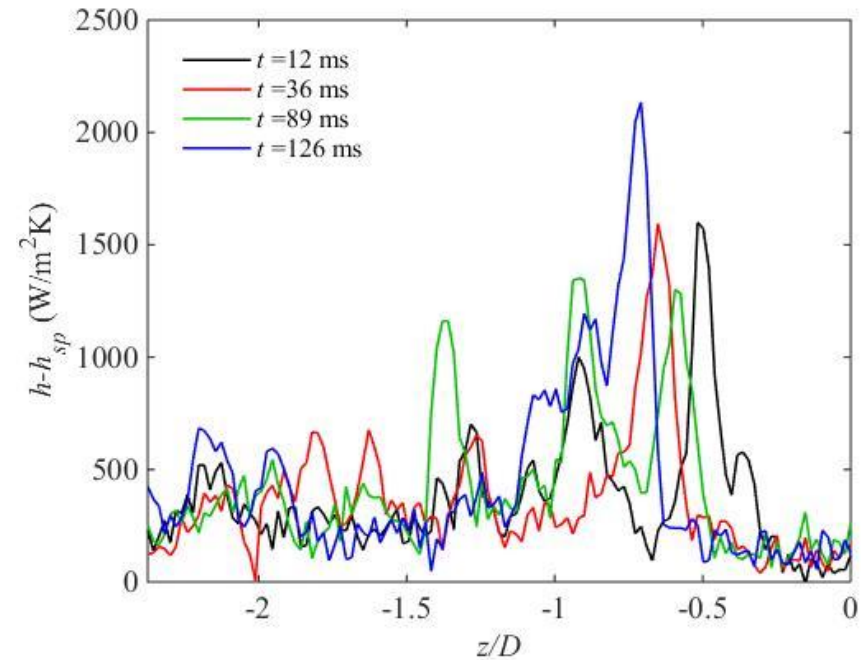


$$Re_F=790, U_d=105 \text{ mm/s}, a/g=1, q''=1.4 \text{ kW/m}^2, h_{sp}=130 \text{ W/m}^2\text{K}$$



Wake history contour plot

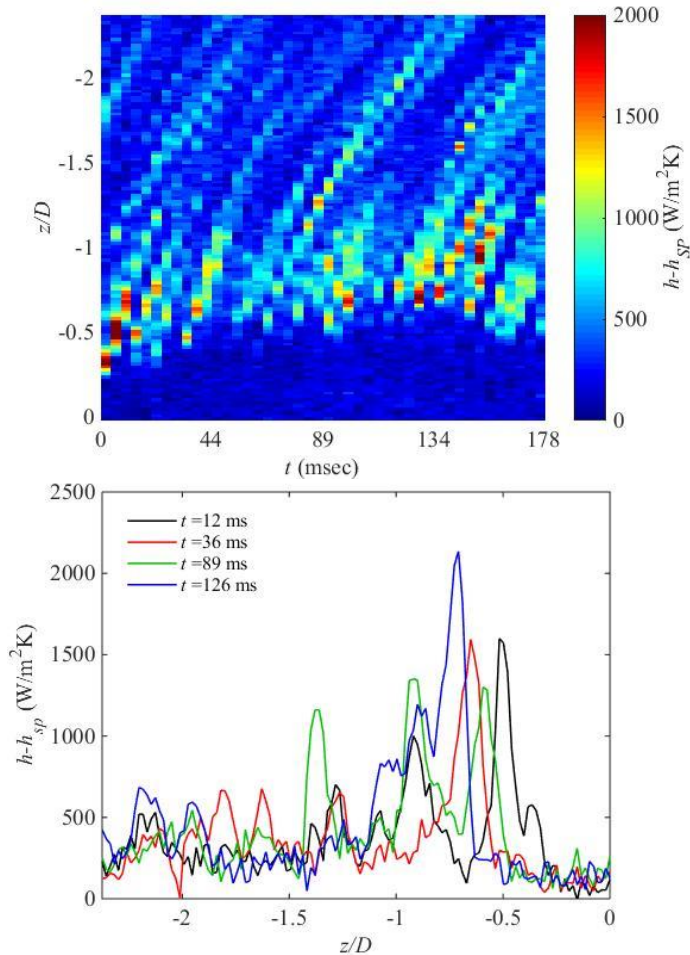
- Streaks indicate vortices moving away from tail
- Penetration length (L_p) is seen to vary with time



Local, time resolved heat transfer profiles

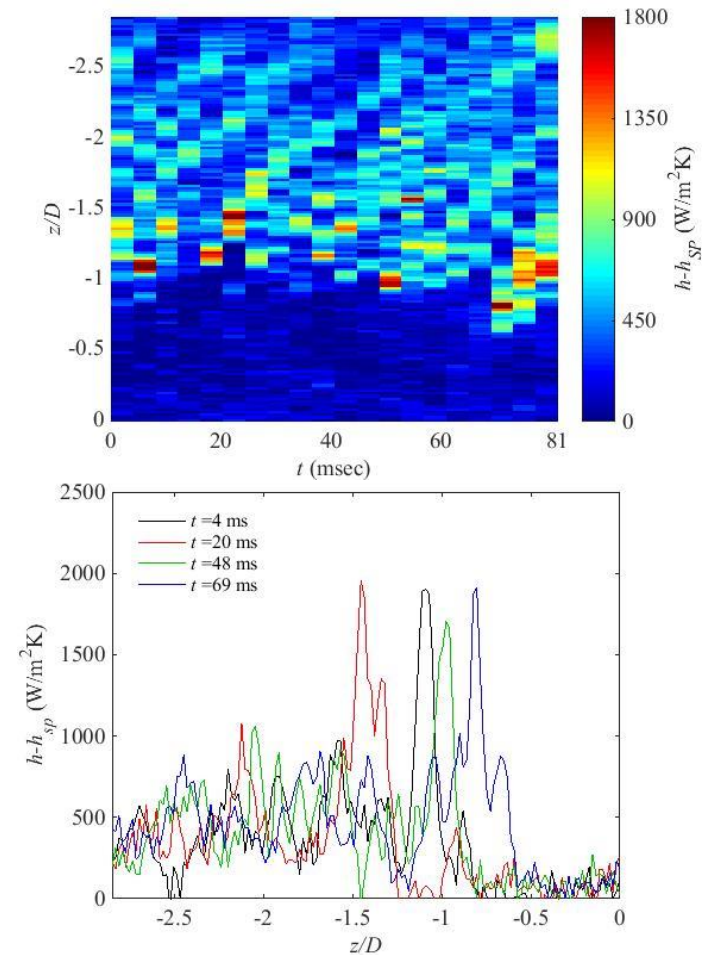
- Variation in peak magnitude and axial position
- Secondary peaks downstream

$a/g=1$, $U_d=105$ mm/s



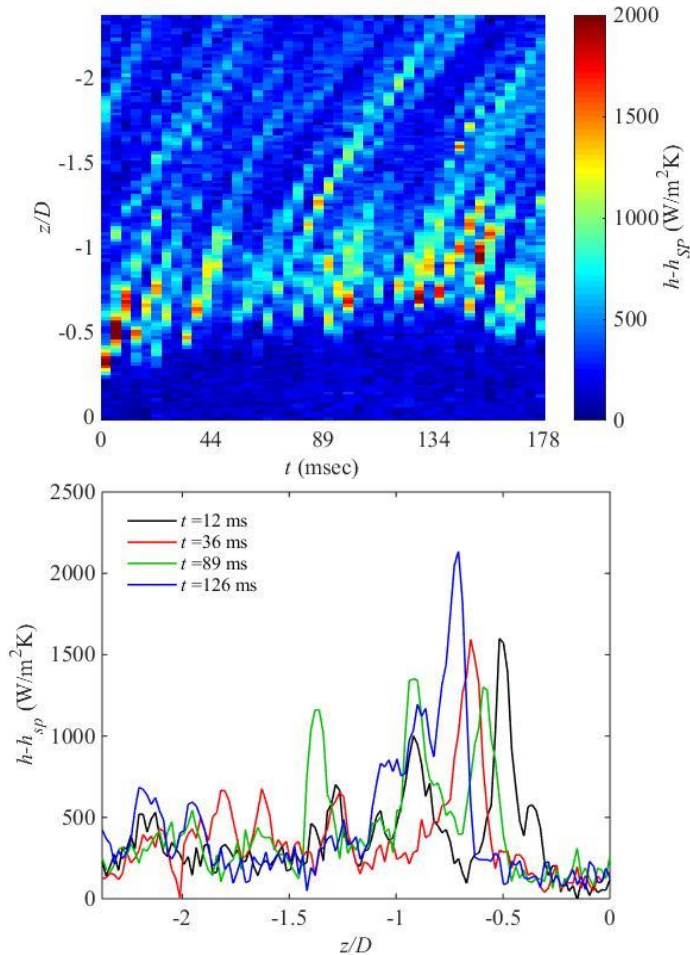
$Re_F=790$, $q''=1.4$ kW/m², $h_{sp}=130$ W/m²K

$a/g=1$, $U_d=163$ mm/s



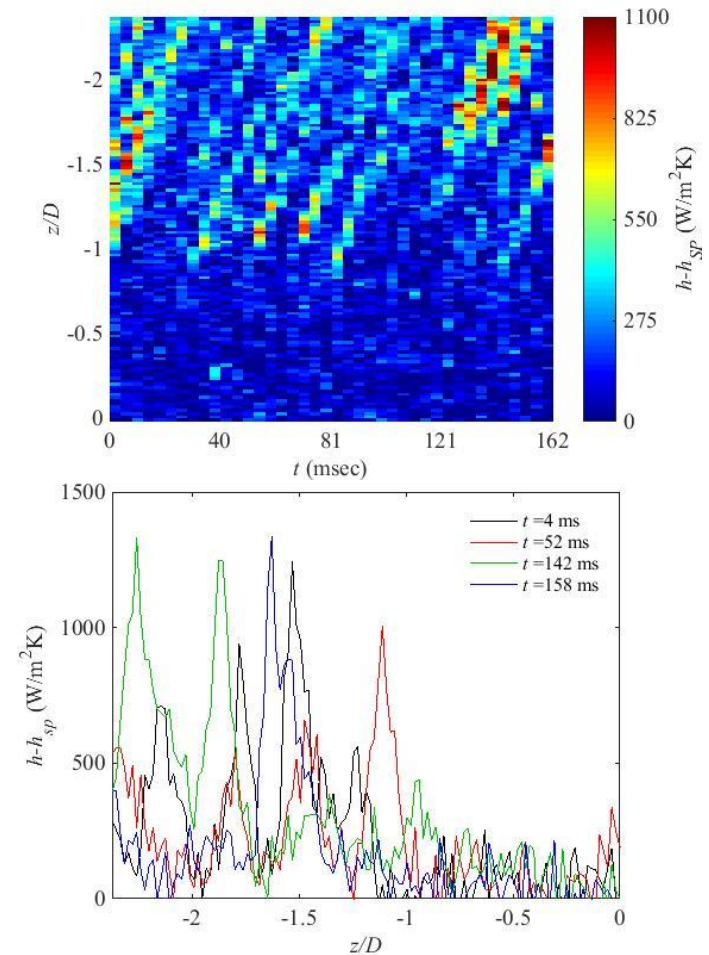
$Re_F=3090$, $q''=1.7$ kW/m², $h_{sp}=192$ W/m²K

$a/g=1$, $U_d=105$ mm/s



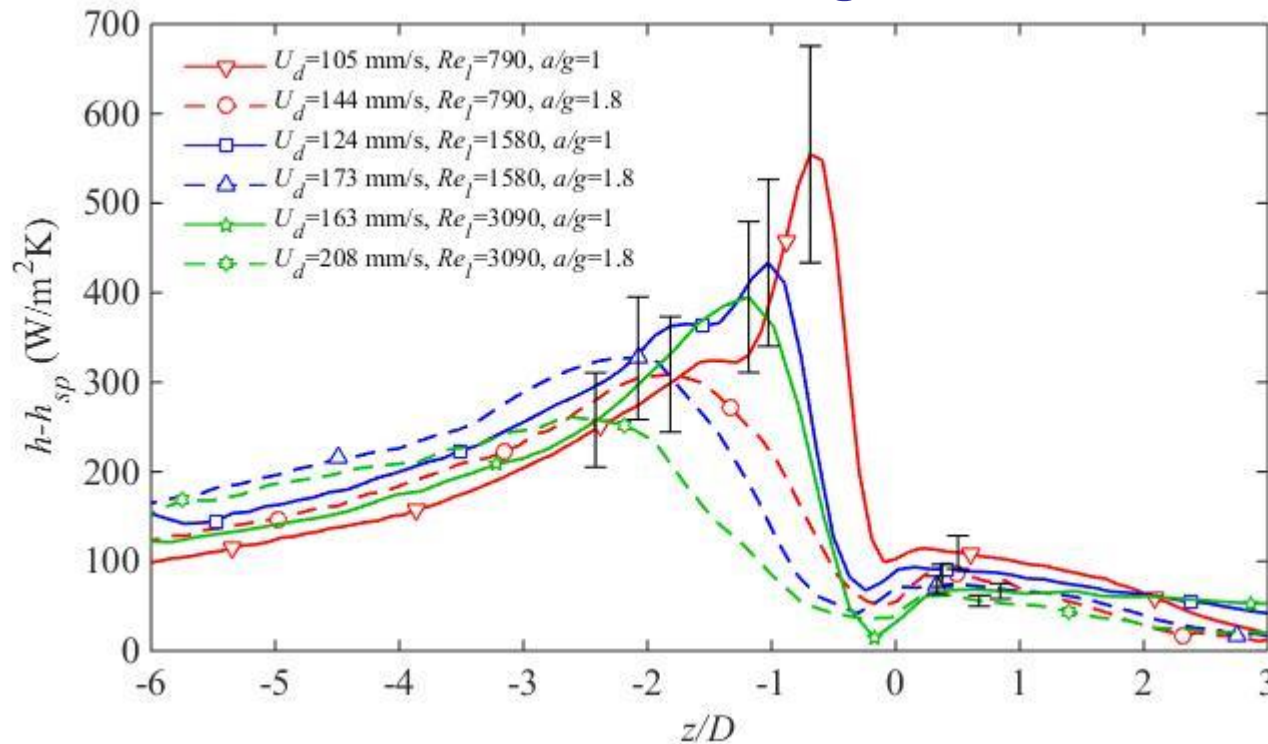
$Re_f=790$, $q''=1.4$ kW/m², $h_{sp}=130$ W/m²K

$a/g=1.8$, $U_d=144$ mm/s



$Re_f=790$, $q''=1.1$ kW/m², $h_{sp}=104$ W/m²K

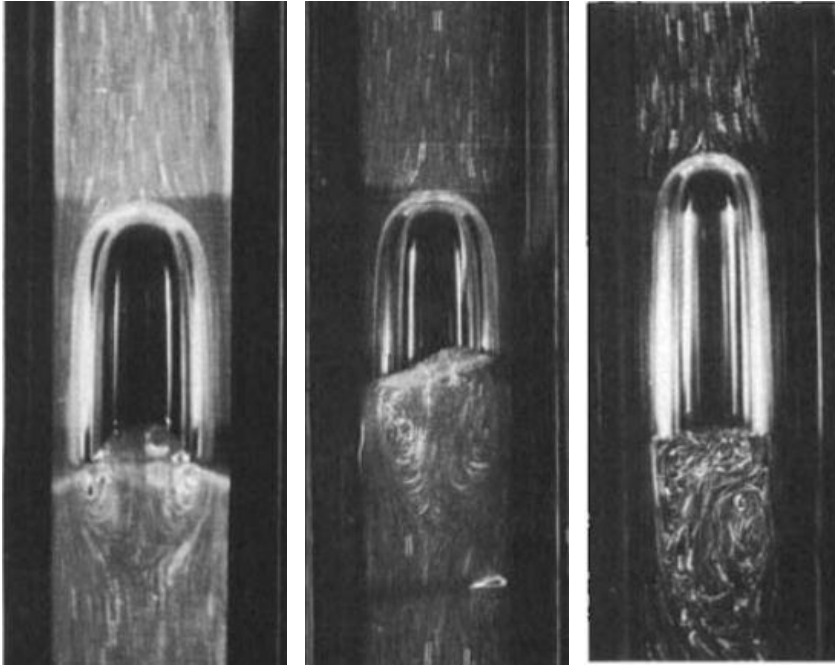
Near-wake region



Near-wake behavior:

- Broadening of profile
- Decrease in peak magnitude
- Shift of peak location downstream

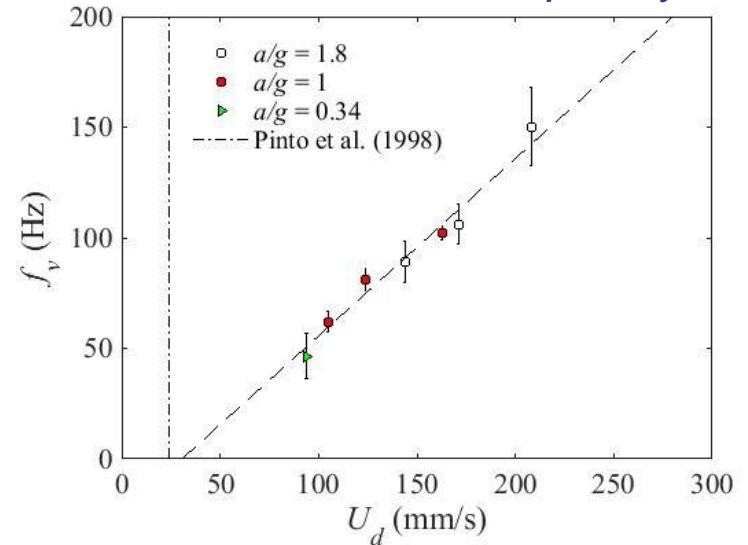
Campos and Carvalho (1988)



- Pinto et al. (1998) suggested that turbulence in the wake occurred when

$$Re_{U_d} = \frac{\rho U_d D}{\mu} > 525$$

Vortex Streak Frequency



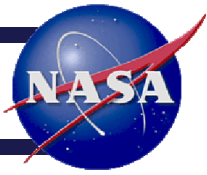
- Present results predict an onset of vortices at $Re_{U_d} = 741$
- A Strouhal number can be assigned

$$St = \frac{f_v \delta}{(U_d - U_{d,cr})} = 0.19 \pm 0.01$$

- Identification of main heat transfer mechanisms for flow boiling regimes necessary for development of prediction models
- An experimental study was conducted to determine the effect of flow parameters and gravity on rising Taylor bubbles
- The drift velocity was found to have a strong effect on the bubble shape and the heat transfer profiles
- Characteristics of the wake structure were identified (vortex frequency and penetration length) were identified and characterized
- These results can be used as validation for numerical simulations and physics-based model predictions



Acknowledgements



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Thank you!